Idealized Body Modeling of a Methane Hydrate, Methane Chimney and Basement High System Based off Gravity Observations in the Central Aleutian Basin

Senior Thesis

Submitted in partial fulfillment of the requirements for the

Bachelor of Science Degree

At The Ohio State University

By

Nick Steed

The Ohio State University

2016

Approved by

Professor Ralph R.B. von Frese, Advisor

School of Earth Sciences

TABLE OF CONTENTS

Abstract……………………………………………………………………..ii

Acknowledgements…………………………………………………………iii

List of Figures………………………………………………………………iv

List of Tables……………………………………………………………..v

Introduction……………………………………………………………....1

Geologic Setting………………………..…………………………….………5

Geology………………………….…….……………..……….……..5

Thermal Environment.…………………….…..……………………5

Methods

Bureau Gravimetrique International Data Collection....……………..……..7

Idealized Body Calculations and Variable Determination…..…..………..7

Microsoft Excel……………………………………………..………..8

Results

Bureau Gravimetrique International Data ..…………..…………………9

MATLAB Data…………..…………………………………………..13

Microsoft Excel Data……………………………………………………..18

Discussion……………………………………………..………………..20

Conclusion………………………………………………..………………22

Suggestions for Future Research…………………...……………………..……..23

References Cited…..……….……………………………………………...……24

Abstract

In this study, I modeled a known methane hydrate deposit and methane chimney in the Central Aleutian Basin which has an associated basaltic basement high that protrudes 3000 meters into the overlying sedimentary strata. The net gravity anomaly in area is negative due to the methane hydrate and free methane gas displacing seawater in the sediment pore space. Modeling was achieved by approximating individual layers with an infinite vertical cylinder at the top of the layer and subtracting from it an infinite vertical cylinder at the base to produce the total effect on the gravitational acceleration from each layer. Idealized source gravity equations were applied to each of these vertical cylinders in MATLAB and summed to produce a gravity signal over the area. A free-air gravity anomaly map was created in a geophysical software program and a profile was taken over the surface of the study area. This profile was plotted vs. distance and a linear trend was fit to the data, then subtracted from each gravity observation point to yield the residual gravity. The observed residual gravity data was plotted against the MATLAB generated theoretical gravity for the infinite vertical cylinders. While the approximations were not perfect, it was successful in producing a signal that was only a few milligals off from the observed data. With some refinement to the code this approach to modeling is a cheap and effective method to reinforce seismic or magnetic data to produce a complete picture of the subsurface.

Acknowledgements

I would like to show my gratitude to my research advisor, Dr. Ralph von Frese, who inspired me to pursue this topic and guided me through the process from start to finish.

I wish to express my thanks to all the professors of the School of Earth Science for their wealth of knowledge and for always offering a helping hand when it was needed.

Finally, I'd like to thank my parents for their utmost, constant support and always challenging me to be the best student and person I could be.

List of Figures

1. Seismic profile of line MCS05

2. Gravity profile of line MCS05

3. Map view of study area

4. Bathymetric map of study area

5. Free-air gravity with profile taken over line MCS05

6. Free-air gravity profile vs. horizontal distance with linear trend

7. Residual free-air gravity anomalies vs. horizontal distance

8. MATLAB generated 2-D and 3-D plots of gas hydrate

9. MATLAB generated 2-D and 3-D plots of methane chimney

10. MATLAB generated 2-D and 3-D plots of basaltic basement

11. Comparison of idealized body modeling vs. residual gravity anomalies from BGI data

List of Tables

1. MATLAB script used to create 2-D and 3-D plots of gravity anomalies vs distance

2. Calculated gravity contributions of individual layers and total gravity

Introduction

Methane hydrate research has been extensive since their discovery because of their economic potential as a future energy source and because their destabilization could lead to submarine landslides and the release of methane into the atmosphere (Li et al, 2011). Gas hydrates, or gas clathrates, are defined as ice-like, crystalline solids where a molecule of gas (generally methane) is trapped in a cage of water molecules. They exist in the pore space of sediments in the shallow waters of polar regions and in deep water oceanic basins which have the low temperature, high pressure conditions suitable for their formation called the Gas Hydrate Stability Zone (GHSZ) (Shankar et al, 2003).

The Aleutian Basin is located in the abyssal portion of the Bering Sea where water depths range from 3000 to 4000 meters. It is bounded by the Aleutian Arc and Beringian Margin which trapped organic terrestrial and marine sediments as they were deposited, beginning in the late Mesozoic. These depositions along with the geothermal gradient, heat flow and relatively undisturbed, thin strata could be responsible for the generation of methane at shallow subsurface depths (Yankovsky et al, 2015).

In the 1970's velocity amplitude structures (VAMPs) were discovered in waters greater than 3700 m depth above apparent basement highs in the Bering Sea. These VAMPs were accompanied by velocity push-downs and shallower pull-ups in the seismic sections. The push-downs represent areas of decreased acoustic velocity caused by methane gas buoyantly rising through the porous rock, forming a methane chimney, until reaching the appropriate temperature and pressure conditions for the formation of stable hydrate, known as the base of the gas hydrate stability zone (BGHSZ). This layer is highly reflective in the seismic section and is called a bottom simulating reflector (BSR) because it mimics the impedence contrast seen between the water-sediment interface at the ocean bottom. The pull-ups are caused by an increase in acoustic velocity due to the solid gas hydrate replacing seawater in the pore space (Scholl and Cooper, 1978).

Evidence for the presence of natural gas was found in 2009 by the Integrated Ocean Drilling Program, Expedition 323, when they recovered cores which released methane gas when brought to the surface (Expedition 323 Scientists, 2010). Furthermore, in 2015, seismic and gravity data was analyzed that was collected for the U.S. Extended Continental Shelf Project in the Aleutian Basin (Figures 1 and 2). They corroborated Scholl and Cooper's hypothesis after finding VAMP structures related to basement highs and BSRs. The corresponding gravity data showed large decreases (up to 10 mGal) around these areas suggesting a regional decrease in density due to the methane hydrate displacing seawater in pore space of the hydrated region (Yankovsky et al, 2015).

In this study, the goal is to create a free-air gravity anomaly map using a geophysical software viewing program, Oasis Montaj, then use idealized source gravity modeling of infinite vertical cylinders to approximate the methane hydrate, methane chimney and the basaltic basement high. An infinite vertical cylinder is calculated at the top of each section (hydrate, free methane gas and basement) then an infinite vertical cylinder calculated at the base will be subtracted, giving the net gravity at each interval. These results will be summed then plotted with the data acquired from Oasis Montaj.

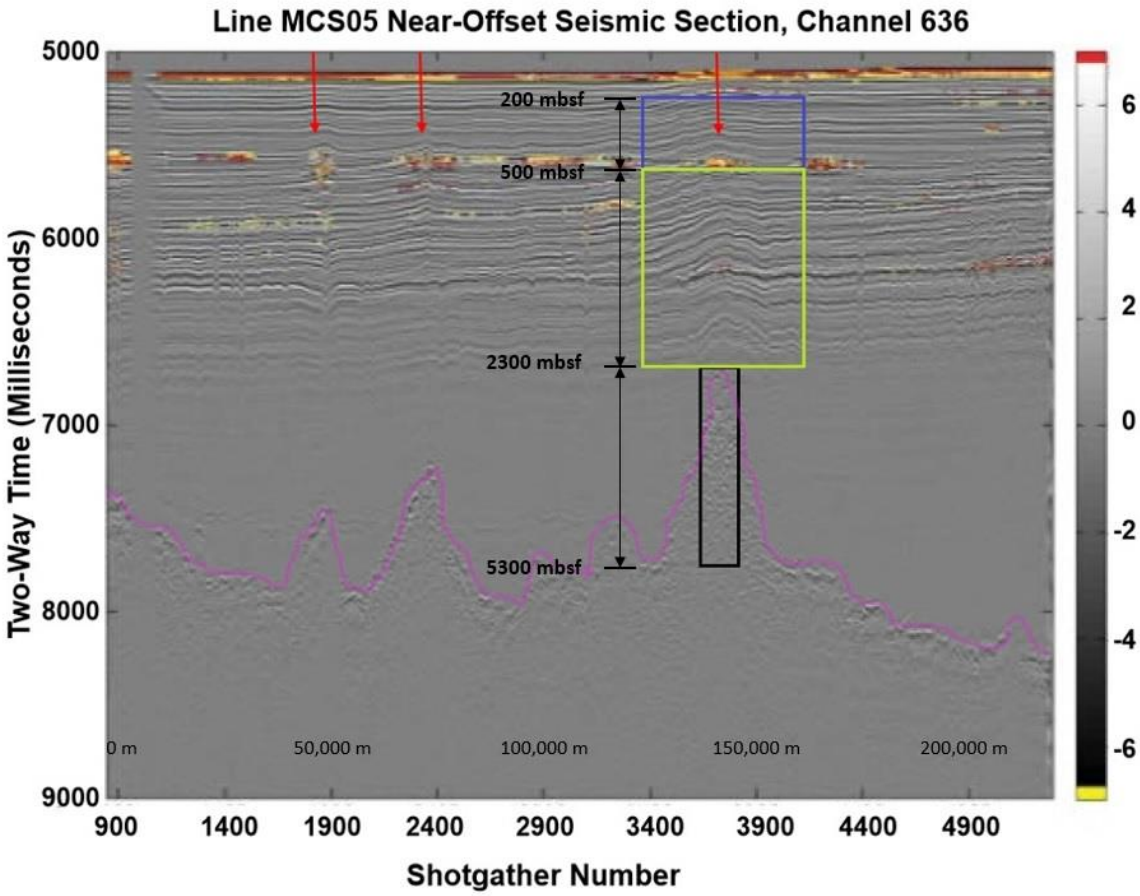

Figure 1. Processed seismic data from a previous study along seismic/gravity line MCS05. Black Box = basaltic basement vertical cylinder (R = 6000 m), Yellow Box = methane gas (R = 19,000 m), Blue Box = methane hydrate vertical cylinder (R = 19,000 m), Red Arrows = VAMP structures, Pink Line = acoustic basement. Shot spacing = 50 m, water depth = 3850 m. Reprinted from Yankovsky EA, Terry DA, Knapp CC (2015) Seismic and Gravity Evidence for Methane-Hydrate Systems in the Central Aleutian Basin. Int J Earth Sci Geophys 1:001.

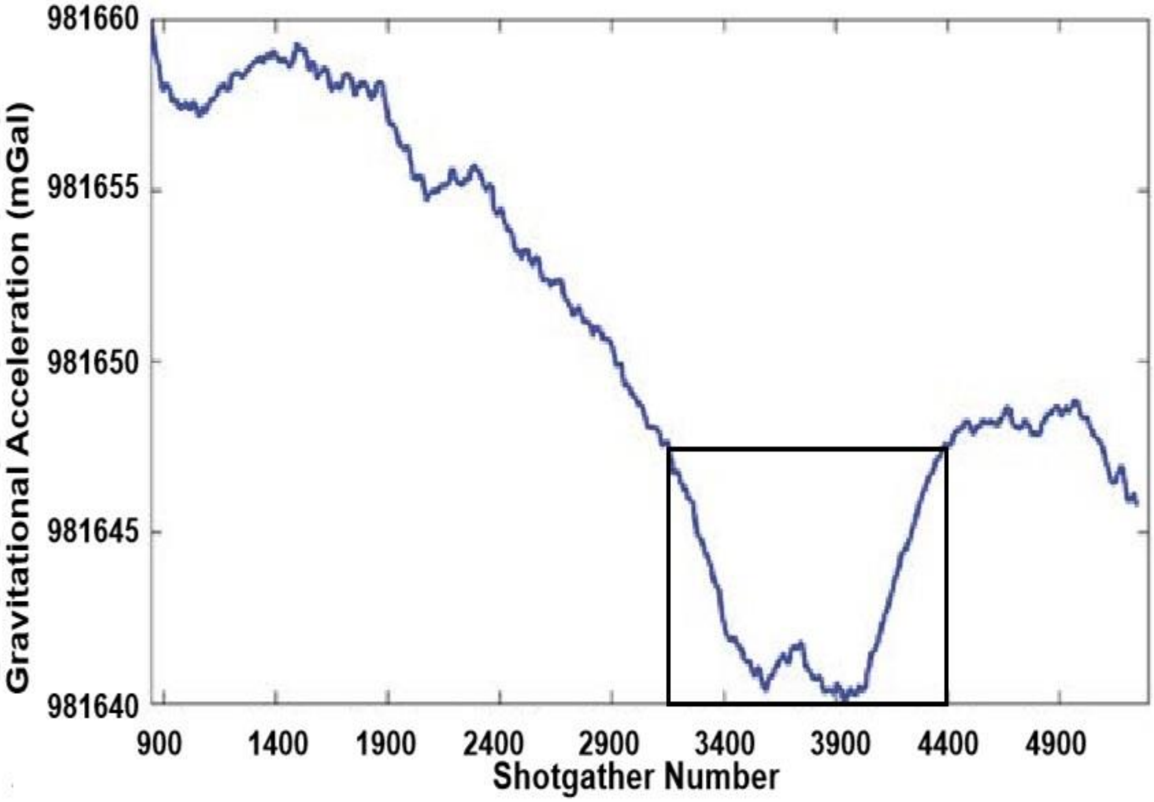

Figure 2. Processed gravity data from previous work, along the seismic/gravity line MCS05. Black Box = portion of the MCS05 line that was attempted to be reproduced in this study. Shot spacing = 50 m. Reprinted from Yankovsky EA, Terry DA, Knapp CC (2015) Seismic and Gravity Evidence for Methane-Hydrate Systems in the Central Aleutian Basin. *Int J Earth Sci Geophys* 1:001.

GEOLOGIC SETTING

Geology

The Bering Sea is a back-arc basin of the Pacific Ocean which has a basaltic, oceanic crust underlying thick sedimentary sequences ranging from 2-9 km in thickness. It is comprised of three phsyiographic areas: the Aleutian, Bowers and Komandorsky Basins (Cooper and Scholl, 1979). The Aleutian Basin is isolated from the Bowers and Komandorsky Basins by the Bowers Ridge to the south and Shirshov Ridge to the west (Figure 3). The basaltic basement was formerly a part of the Kula Plate which was being subducted under Kamchatka (60 Ma), then it was fractured by the formation of the Aleutian Ridge around 55 Ma and remains as a remnant of the former oceanic crust (Yankovsky et al, 2015). Overlying this feature is a sedimentary section that can be divided into three units. The uppermost is Pleistocene to late Pliocene in age and consists of turbidite-bearing diatom clays (0~375 mbsf). The middle portion (~240 m thick) is middle to early Pliocene and made of semi-consolidated diatom clays, while the bottom section is Miocene in age and contains consolidated mudstone with interbedded carbonate layers and extends to the basement (Cooper and Scholl, 1979).

Thermal environment

The Aleutian Basin has an observed heat flow value of 1.44 ± 0.22 microcal/cm^2/s and a thermal conductivity of 2.5 mcal/cm/ sec/°C which gives a geothermal gradient of 58°C/km (Cooper and Scholl, 1979). This means that thermogenic hydrocarbon generation (50 to 100°C) can occur at sub-bottom depths of 0.9-1.8 km. Applying temperature vs depth and age curves of known oil and gas producing basins, hydrocarbon generation could occur in sediments as young as Miocene in age (18-23 million years ago) (Cooper and Scholl, 1979).

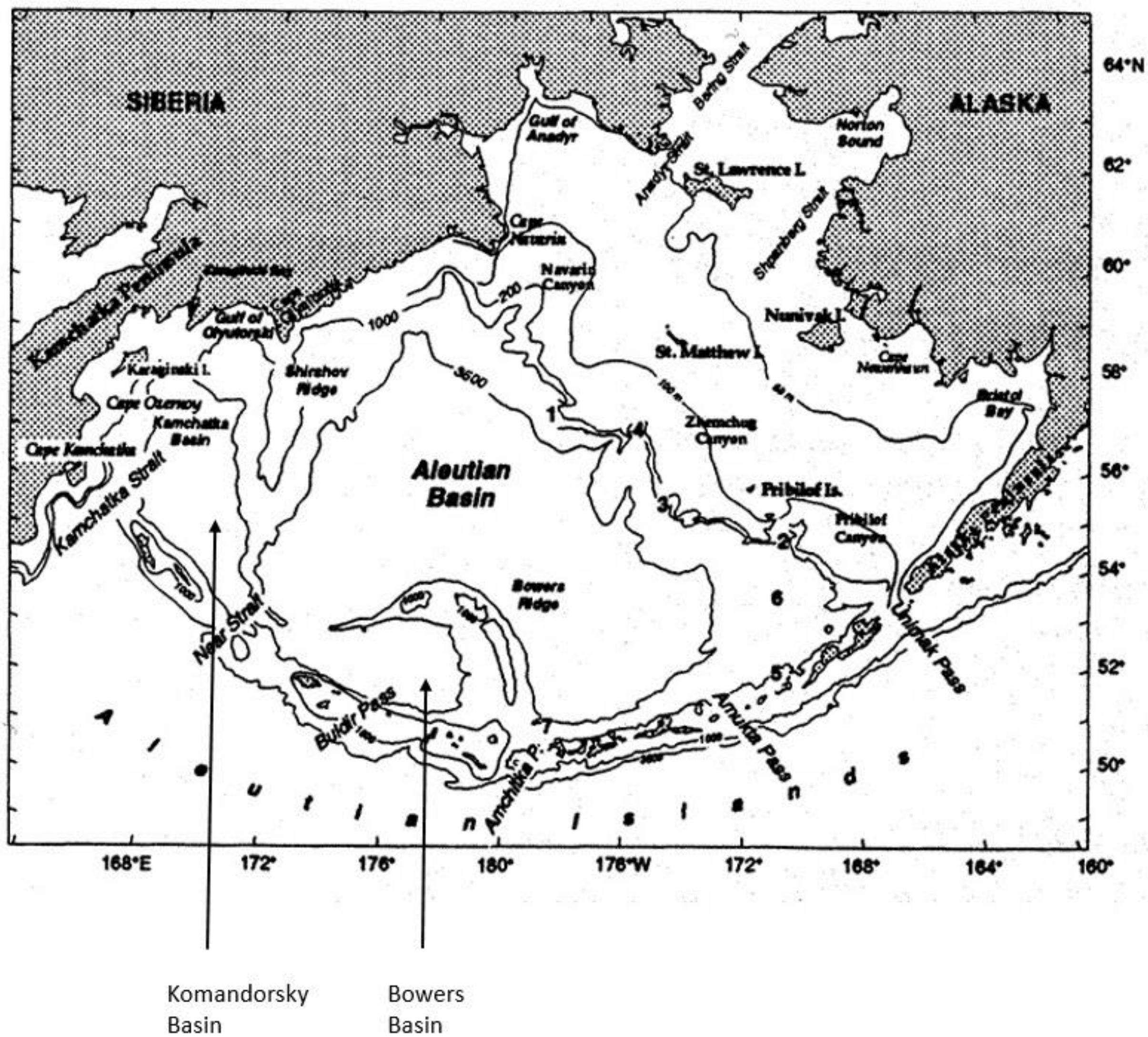

Figure 3. Map view of Bering Sea containing the Aleutian Basin and relevant geologic features. Contour intervals are in meters. Reprinted from Dynamics of the Bering Sea: A Summary of Physical, Chemical, and Biological Characteristics, and a Synopsis of Research on the Bering Sea, T.R. Loughlin and K. Ohtani (eds.), North Pacific Marine Science Organization (PICES), University of Alaska Sea Grant, AK-SG-99-03, 1–28

METHODS

Bureau Gravimetrique International (BGI) data collection

The Bureau Gravimetrique International produced its gravitational data, known as the World Gravity Map 2012 (WGM2012), by deriving it from the EGM 2008 Geopotential Model (which applies spherical harmonic coefficients) and ETOPO1 Global Relief Model (incorporates land topography and oceanic bathymetry) to create high resolution maps (Balmino et al, 2012)

Idealized body calculations and variable determination

The gas hydrate deposit, methane chimney and basaltic basement high are approximated using Nettleton's idealized source gravity modeling equations of an infinite vertical cylinder (von Frese et al, 2013). Here, g_z is the vertical gravity anomaly in gal ($m/s^2 = 10^5$ mGal), G is the gravitational constant (= 6.674 x 10^{-11} m^3 kg^{-1} s^{-2}), $\Delta\sigma$ is the density contrast in kg/m^3 , z is the depth to the top of the source in meters, R is the radius of the cylinder in meters and x is the lateral distance from the center of the cylinder in meters. Equation 1 is used when calculating the gravity effect directly above the center of the cylinder, Equation 2 is applied for computing gravity effects from just past the center to the edge of the cylinder's radius and Equation 3 is used when computing the gravity effects past the edge of the cylinder.

1) $g_z = 2\pi G\Delta\sigma[(z^2 + R^2)^{\frac{1}{2}} - z]$

$\forall\ (x = 0)$

2) $g_z = 2\pi G\Delta\sigma R\{\frac{1}{2}\left(\frac{R}{\sqrt{x^2+z^2}}\right) - \frac{1}{16}\left(\frac{R}{\sqrt{x^2+z^2}}\right)^3\left(\frac{2z^2-x^2}{x^2+z^2}\right) +$

$\frac{1}{128}\left(\frac{R}{\sqrt{x^2+z^2}}\right)^5\left(\frac{35z^4}{(x^2+z^2)^2} - \frac{30z^2}{x^2+z^2} + 3\right) + \cdots\Big\}$

$\forall\ (0 < x \leq R)$

3) $g_z = 2\pi G \Delta\sigma R\{1 - \left(\frac{z}{R}\right) + \frac{1}{4}\left(\frac{2z^2 - x^2}{R^2}\right) - \frac{1}{8}\left(\frac{8z^4 - 24z^4x^2 + 3x^4}{R^4}\right) + \cdots\}$

$\forall\ (x > R)$

Equations 1-3 were solved via a MATLAB script (Table 1) (Kyle Shalek, Jianbin Duan and Kuo-Hsin Tseng, 2013). The depth to the source was found by manually measuring the distance between a 1000 millisecond interval of the two-way travel time and relating it to the measured distance to the target intervals. Next, a velocity was assigned to the layer (Cooper and Rabinowitz, 1977) and the result was divided by 2 to account for the two-way travel time (Figure 1). A density contrast of 900-1030 kg/m^3 was used to evaluate the methane hydrate displacing seawater, 700-1030 kg/m^3 for the methane gas displacing seawater and 2900-2800 kg/m^3 for the basaltic basement intruding the sedimentary strata. The radius used for the methane hydrate and methane chimney layers was 19,000 m and the radius of the basement high was 6,000 m.

Microsoft Excel

After producing the MATLAB plots, the top and bottom gravity profiles of each layer were input into Microsoft Excel. The bottom gravity was subtracted from the top and multiplied by a factor of 10^5 to convert it from m/s^2 to milligals. Next, the methane hydrate and methane chimney layers were multiplied by 0.38 to account for the rock porosity and the net gravity of the three layers were summed to give the total gravity (Table 2).

Results

Bureau Gravimetrique International (BGI) Data

BGI bathymetric data was used to create a map (Figure 4) to try and relate ocean bottom features to the observed gravity. A free-air gravity data set was extracted to produce a map of gravity anomalies on a geographic coordinate system (Figure 5). Next, a profile was taken in a SW-NE direction along the coordinates of line MCS05 in Figure 5 to obtain regional anomaly values.

The data generated by the profile in Figure 5 was then plotted against the horizontal extent of line MCS05, which exhibited a minimum negative gravity anomaly of -15.6 mGals (Figure 6). A linear trend was fit to the data and subtracted from individual anomalies to remove the regional effects and leave the residual gravity (Figure 7), which has a minimum negative anomaly of -6.9 mGals.

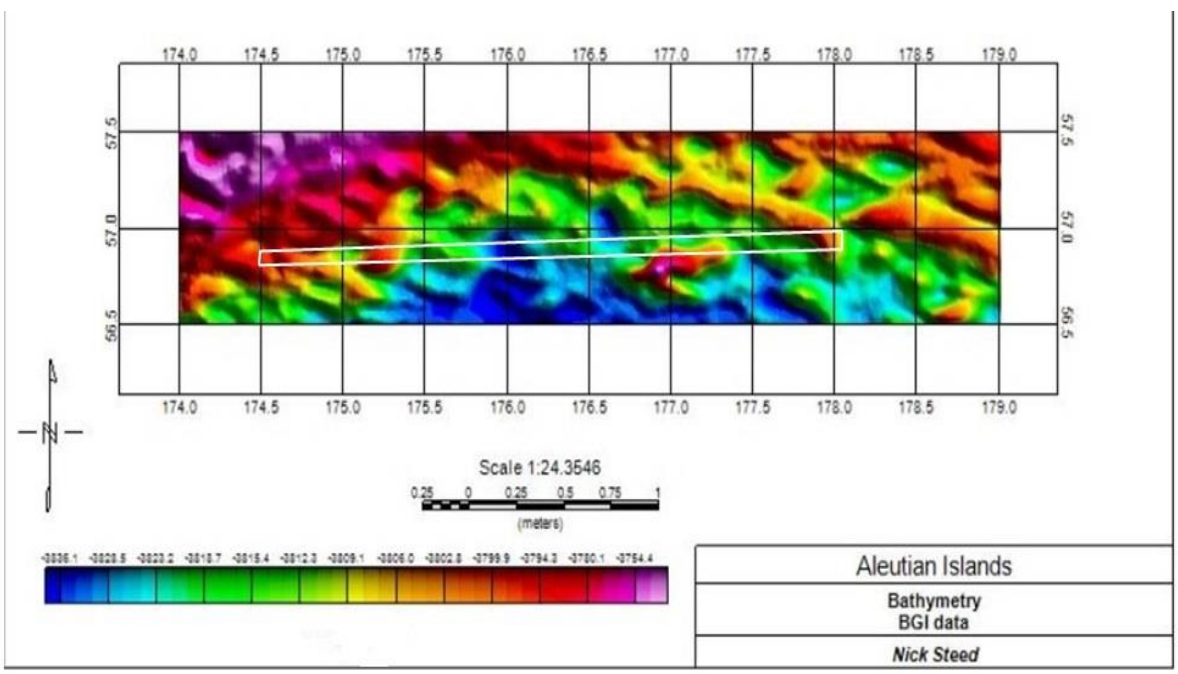

Figure 4. Seafloor topographic map. White box encompasses the coordinates of line MCS05. Color bar indicates water depth.

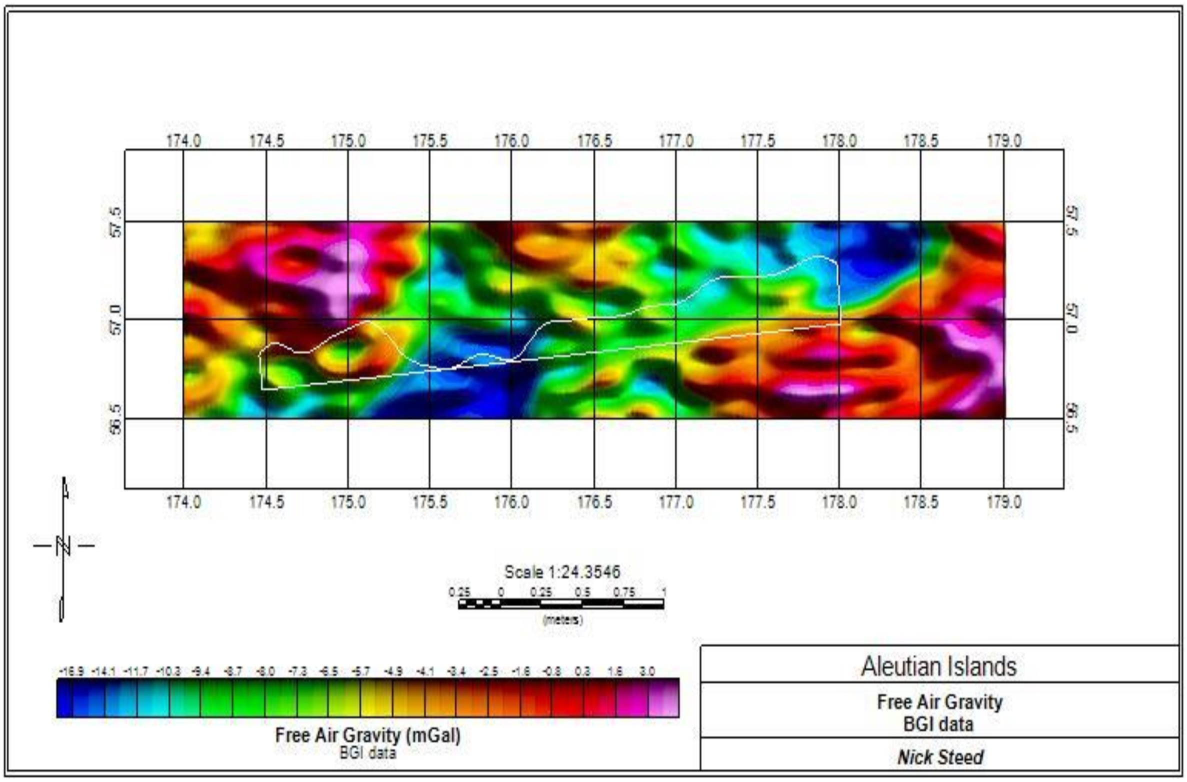

Figure 5. Free-air gravity anomalies plotted on a geographic coordinate system of the study area. A profile was taken in a SW-NE direction along line MCS05 (straight white line). The curved white line above it is the graphical representation of the free-air gravity anomalies. Color bar indicates magnitude of the anomalies (blue = negative and pink = positive)

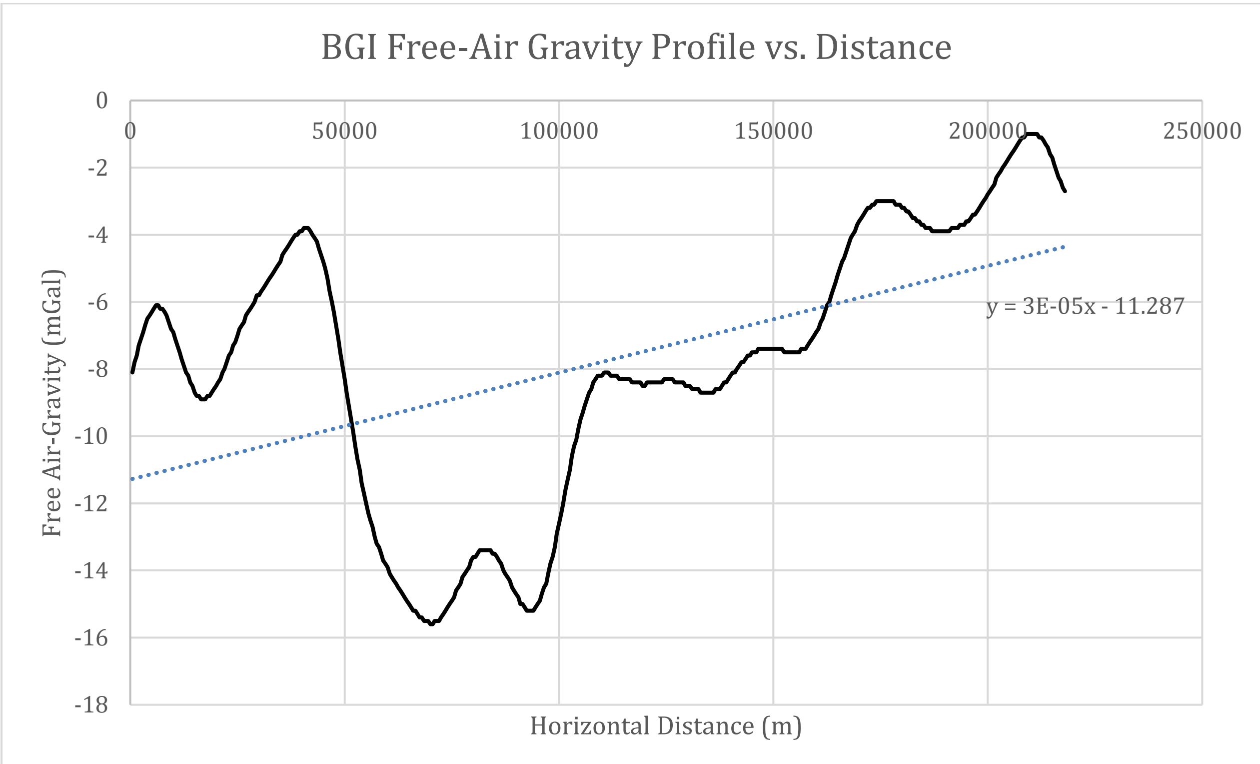

Figure 6. Plot of the gravity profile taken in Figure 5. The minimum free-air anomaly is -15.6 mGal. The blue dotted line is a linear trend that was fit to the data with the equation of the line displayed beneath it.

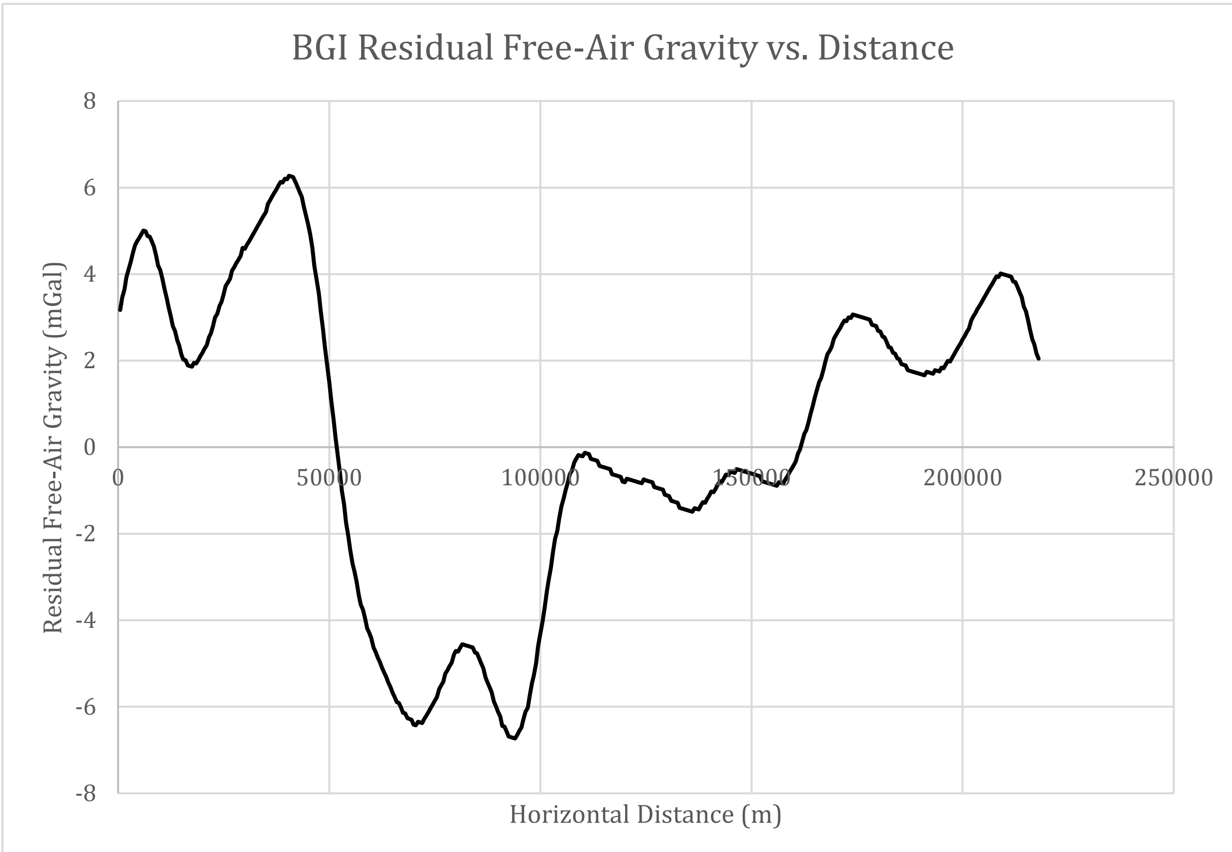

Figure 7. BGI free-air gravity anomalies plotted against horizontal distance along MCS05. Linear trend values have been subtracted from the free-air anomalies to remove the regional effect, leaving the residual gravity anomalies. Minimum residual gravity anomaly = -6.9 mGal.

MATLAB Data

Variable parameters (radius [R], density contrast [Δσ], depth to top of source [z] and distance from the center of the source [x]) were entered into a MATLAB script (Table 1) to produce 2-D and 3-D plots of the gravity effect from infinite vertical cylinders applied to the methane hydrate (Figure 8), methane chimney (Figure 9) and basaltic basement high (Figure 10).

```
%Gravity of a infinite vertical cylinder %%%%%%%%%%%%%%%%%%%%%%%%%
G = 6.673E-11;
density = 100;
R = 6000;
z = 2300;
x_profile = -32500:500:32500;
r=sqrt(z^2+x_profile.^2);
cos_theta=z./r;
x = -32500:500:32500;
y = -32500:500:32500;
P=legendre(1,cos_theta);
P1=P(1,:);
P=legendre(2,cos_theta);
P2=P(1,:);
P=legendre(4,cos_theta);
P4=P(1,:);
for i=1:131;
if r(i)<R
g_profile(i) = 2*pi*G*density*R*(1-r(i)/R*P1(i)+0.5*(r(i)/R)^2*P2(i)-0.125*(r(i)/R)^4*P4(i));
else
g_profile(i) = 2*pi*G*density*R*(0.5*R/r(i)-0.125*(R/r(i))^3*P2(i)+1/16*(R/r(i))^5*P4(i));
end;
end;
g_profile(66)=2*pi*G*density*(sqrt(z^2+R^2)-z);
g_profile = g_profile(:);
subplot(1,2,2)
%figure;
plot(x_profile,g_profile)
xlabel('distance (m)')
ylabel('gravity')
title('v-cylinder Gravity Profile')
%3D contour
for j=1:131
```

```
for k=1:131
distance(j,k) = sqrt((x(j)^2) + (y(k)^2) );
end;
end;
r_3d=sqrt(z^2+distance.^2);
cos_theta_3d=z./r_3d;
P_3d=legendre(1,cos_theta_3d);
P1_3d(:,:)=P_3d(1,:,:);
P_3d=legendre(2,cos_theta_3d);
P2_3d(:,:)=P_3d(1,:,:);
P_3d=legendre(4,cos_theta_3d);
P4_3d(:,:)=P_3d(1,:,:);
for i=1:131;
for j=1:131;
if r_3d(i,j)<R
g(i,j) = 2*pi*G*density*R*(1-r_3d(i,j)/R*P1_3d(i,j)+0.5*(r_3d(i,j)/R)^2*P2_3d(i,j)-0.125*(r_3d(i,j)/R)^4*P4_3d(i,j));
else
g(i,j) = 2*pi*G*density*R*(0.5*R/r_3d(i,j)-0.125*(R/r_3d(i,j))^3*P2_3d(i,j)+1/16*(R/r_3d(i,j))^5*P4_3d(i,j));
end;
end;
end;
g(66,66)=2*pi*G*density*(sqrt(z^2+R^2)-z);
distance = [distance(1:131,1:131)];
g = [g(1:131,1:131)]/(10^(-5)); %milliGal
average = mean2(g);
std_dev = std2(g);
g_max1 = max(g);
g_min1 = min(g);
g_max = max(g_max1);
g_min = min(g_min1);
subplot(1,2,1)
%figure;
[C,h] = contourf(x,y,g);
colormap cool
colorbar;
xlabel('distance (m)')
ylabel('distance (m)')
title('v-cylinder Gravity Contour')
title({'v-cylinder Gravity Contour (mGals)';['max=',num2str(g_max),' min=',num2str(g_min)];...
['average=',num2str(average),' std.dev.=',num2str(std_dev)]})
```

Table 1. MATLAB script of an infinite vertical cylinder used to calculate the gravity of methane hydrate, methane chimney and basaltic basement high.

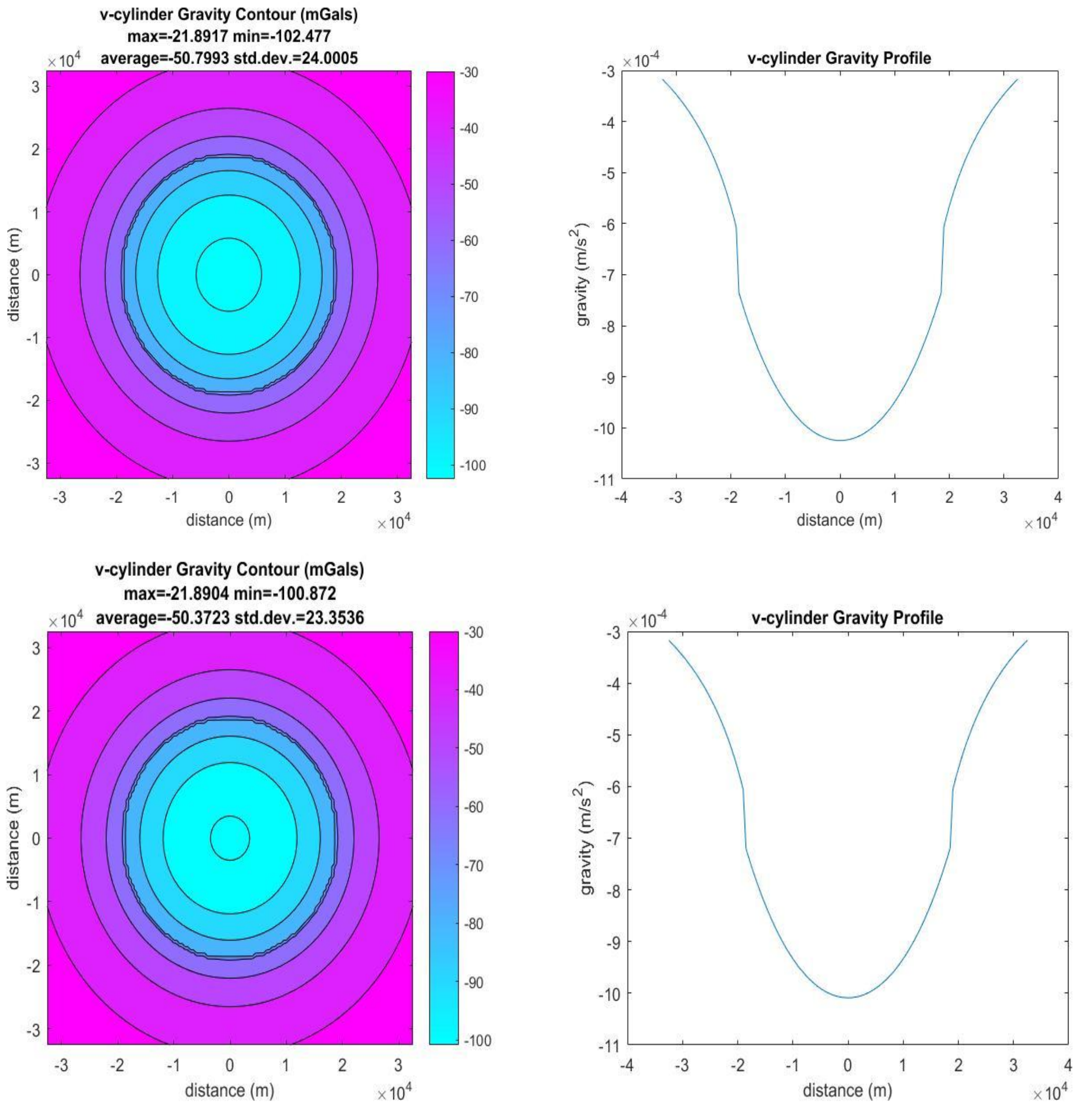

Figure 8. MATLAB generated plots for gravity effects of the infinite vertical cylinders of gas hydrate. Left = 3-D contour plot with distances in meters (x 10^4) and gravity in milligals. Statistics listed above plot. Right = 2-D plot of gravity in Gals (x10^5 = milligals) and distance in meters (x 10^4) Top plot = top of deposit. Bottom plot= base of deposit.

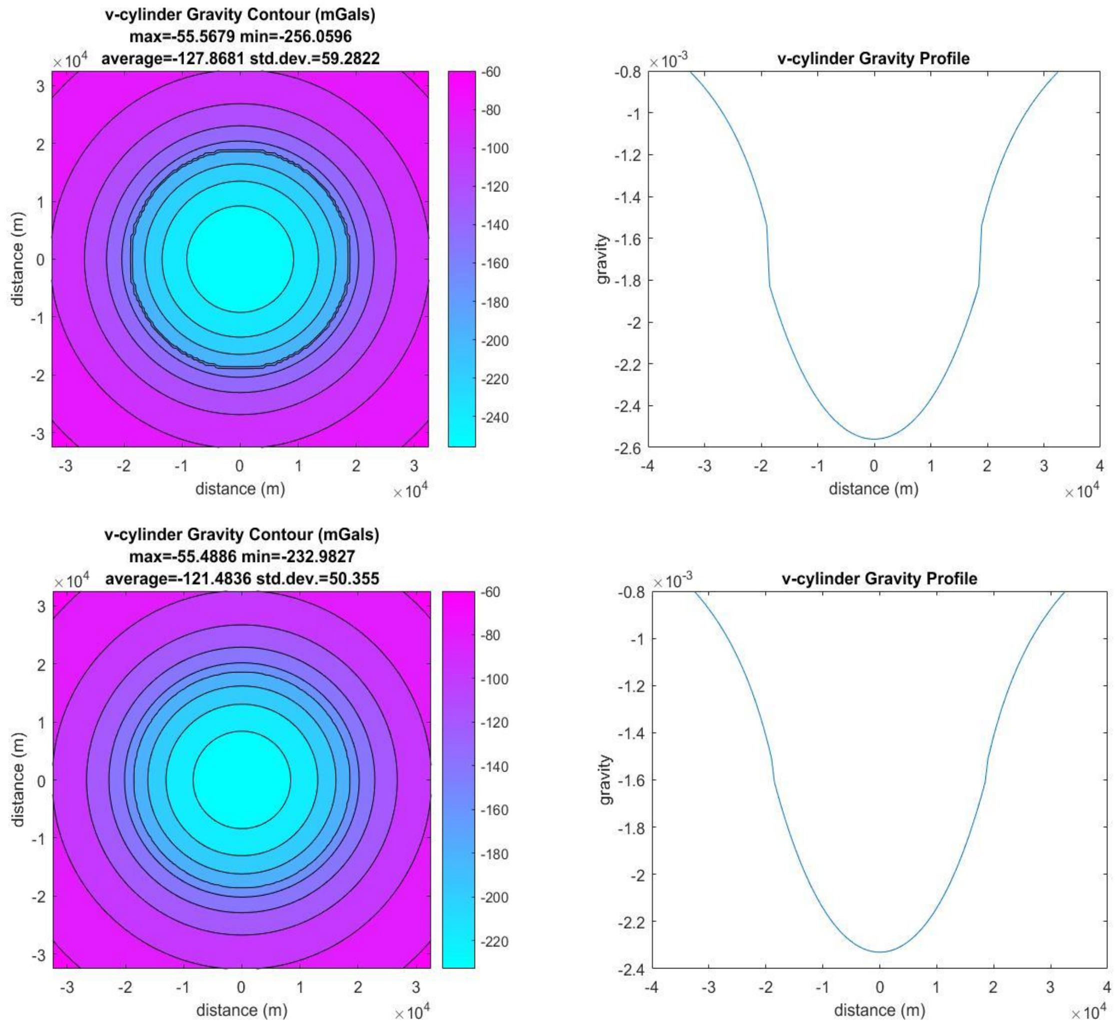

Figure 9. MATLAB generated plots for gravity effects of infinite vertical cylinder of methane chimney. Left = 3-D contour plot with distances in meters (x 10^4) and gravity in milligals. Statistics listed above plot. Right = 2-D plot of gravity in Gals (x10^5 = milligals) and distance in meters (x 10^4) Top plot = top of deposit. Bottom plot= base of deposit.

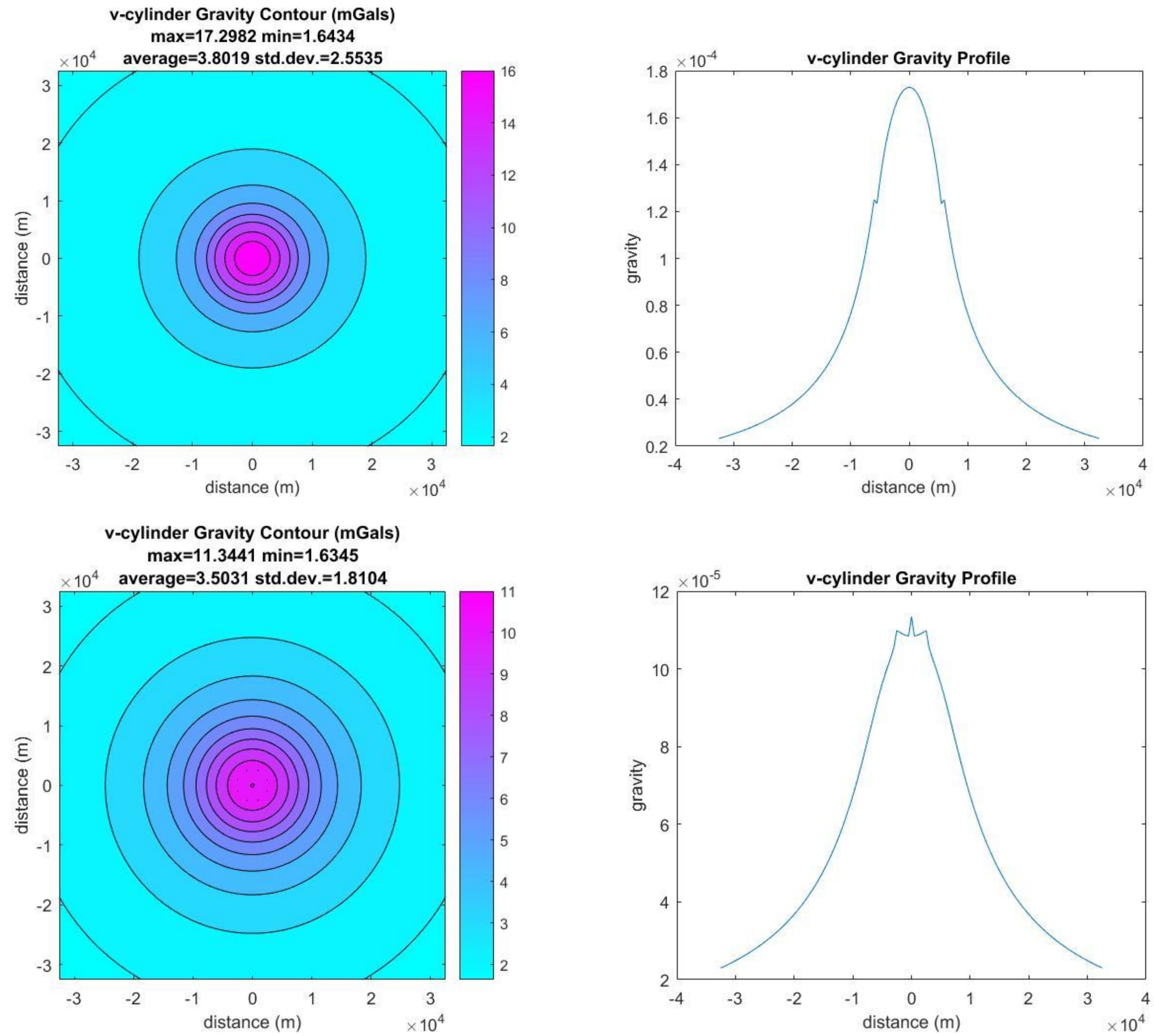

Figure 10. MATLAB generated plots for gravity effects of infinite vertical cylinder of basaltic basement. Left = 3-D contour plot with distances in meters (x 10^4) and gravity in milligals. Statistics listed above plot. Right = 2-D plot of gravity in Gals (x10^5 = milligals) and distance in meters (x 10^4) Top plot = top of deposit. Bottom plot= base of deposit.

Microsoft Excel Data

Table 2 shows the data generated from an Excel spreadsheet, which was used to calculate the gravity effect of the hydrate, methane chimney and basement.

	A	B	C	D	E	F	G	H	I	J
1	Hydrate Top (m/s^2)	Hydrate Bottom (m/s^2)	Net Hydrate (mGal)	Chimney Top (m/s^2)	Chimney Bottom (m/s^2)	Net Chimney (mGal)	Basement Top (m/s^2)	Basement Bottom (m/s^2)	Net Basement (mGal)	Total Gravity (mGal)
2	-0.000317299	-0.000317254	-0.001739073	-0.000805336	-0.000802567	-0.105225309	0.00002326	0.00002301	0.02541240	-0.08155198
3	-0.000322778	-0.00032273	-0.001846829	-0.000819237	-0.000816297	-0.111709379	0.00002363	0.00002336	0.02663322	-0.08692299
4	-0.00032846	-0.000328408	-0.001963959	-0.000833652	-0.000830527	-0.118753609	0.00002400	0.00002372	0.02793363	-0.09278394
5	-0.000334357	-0.000334302	-0.002091522	-0.000848612	-0.000845285	-0.126420582	0.00002439	0.00002410	0.02932024	-0.09919186
6	-0.000340482	-0.000340423	-0.002230719	-0.00086415	-0.000860603	-0.134781453	0.00002479	0.00002448	0.03080033	-0.10621185
7	-0.000346849	-0.000346786	-0.002382922	-0.000880303	-0.000876515	-0.143917346	0.00002521	0.00002488	0.03238190	-0.11391836
8	-0.000353473	-0.000353406	-0.002549704	-0.000897108	-0.000893057	-0.153920997	0.00002564	0.00002530	0.03407384	-0.12239686
9	-0.000360372	-0.0003603	-0.002732868	-0.000914609	-0.000910269	-0.164898723	0.00002608	0.00002572	0.03588593	-0.13174566
10	-0.000367564	-0.000367487	-0.00293449	-0.000932852	-0.000928195	-0.176972769	0.00002654	0.00002616	0.03782905	-0.14207820
11	-0.000375069	-0.000374986	-0.003156972	-0.000951888	-0.00094688	-0.19028412	0.00002702	0.00002662	0.03991529	-0.15352580
12	-0.000382909	-0.000382819	-0.003403092	-0.000971773	-0.000966378	-0.204995895	0.00002751	0.00002709	0.04215806	-0.16624093
13	-0.000391108	-0.000391011	-0.003676085	-0.000992567	-0.000986744	-0.221297434	0.00002802	0.00002758	0.04457235	-0.18040117
14	-0.000399693	-0.000399588	-0.003979723	-0.001014339	-0.001008039	-0.239409263	0.00002855	0.00002808	0.04717489	-0.19621410
15	-0.000408693	-0.00040858	-0.004318425	-0.001037164	-0.001030332	-0.259589137	0.00002910	0.00002860	0.04998440	-0.21392316
16	-0.000418142	-0.000418018	-0.004697385	-0.001061123	-0.001053699	-0.282139425	0.00002968	0.00002915	0.05302189	-0.23381492
17	-0.000428075	-0.00042794	-0.005122733	-0.00108631	-0.00107822	-0.307416182	0.00003027	0.00002971	0.05631098	-0.25622794
18	-0.000438533	-0.000438386	-0.005601734	-0.001112826	-0.001103988	-0.335840334	0.00003090	0.00003030	0.05987827	-0.28156380
19	-0.000449562	-0.000449401	-0.006143033	-0.001140786	-0.001131104	-0.367911538	0.00003154	0.00003091	0.06375383	-0.31030074
20	-0.000461213	-0.000461035	-0.006756963	-0.00117032	-0.001159682	-0.404225436	0.00003222	0.00003154	0.06797169	-0.34301071
21	-0.000473542	-0.000473346	-0.007455934	-0.001201571	-0.001189847	-0.445495238	0.00003292	0.00003220	0.07257048	-0.38038069
22	-0.000486616	-0.000486398	-0.008254921	-0.001234704	-0.001221741	-0.492578877	0.00003366	0.00003288	0.07759419	-0.42323961
23	-0.000500506	-0.000500265	-0.00917208	-0.001269904	-0.001255522	-0.546513324	0.00003443	0.00003360	0.08309302	-0.47259239
24	-0.000515299	-0.000515029	-0.01022955	-0.001307383	-0.001291368	-0.608558229	0.00003524	0.00003435	0.08912443	-0.52966334
25	-0.000531088	-0.000530787	-0.011454463	-0.001347382	-0.001329481	-0.680251722	0.00003608	0.00003512	0.09575443	-0.59595176
26	-0.000547986	-0.000547647	-0.01288027	-0.001390181	-0.00137009	-0.763482206	0.00003697	0.00003594	0.10305901	-0.67330347
27	-0.000566119	-0.000565737	-0.014548453	-0.0014361	-0.001413454	-0.860581297	0.00003790	0.00003679	0.11112601	-0.76400374
28	-0.000585637	-0.000585202	-0.01651078	-0.001485513	-0.00145987	-0.974444942	0.00003888	0.00003768	0.12005726	-0.87089846
29	-0.000606711	-0.000606215	-0.018832279	-0.001538853	-0.001509677	-1.108692334	0.00003991	0.00003861	0.12997127	-0.99755334
30	-0.000735722	-0.000719886	-0.601785671	-0.001827402	-0.001609681	-8.273411773	0.00004100	0.00003959	0.14100644	-8.73419100
31	-0.000753338	-0.00073749	-0.602219662	-0.00187209	-0.001653672	-8.29985183	0.00004215	0.00004062	0.15332501	-8.74874649
32	-0.000770233	-0.000754374	-0.602641763	-0.001914949	-0.001695855	-8.325567503	0.00004337	0.00004170	0.16711794	-8.76109133
33	-0.000786427	-0.000770557	-0.603051973	-0.00195603	-0.001736278	-8.35055879	0.00004466	0.00004283	0.18261092	-8.77099985
34	-0.00080194	-0.000786059	-0.603450294	-0.001995382	-0.001774991	-8.374825693	0.00004602	0.00004402	0.20007182	-8.77820417
35	-0.00081679	-0.000800899	-0.603836724	-0.002033052	-0.001812042	-8.39836821	0.00004748	0.00004528	0.21981998	-8.78238495
36	-0.000830995	-0.000815094	-0.604211264	-0.002069086	-0.001847476	-8.421186342	0.00004903	0.00004660	0.24223784	-8.78315977
37	-0.000844573	-0.000828663	-0.604573914	-0.002103529	-0.001881338	-8.443280089	0.00005068	0.00004800	0.26778554	-8.78006846
38	-0.000857541	-0.000841622	-0.604924674	-0.002136425	-0.001913671	-8.464649451	0.00005245	0.00004948	0.29701942	-8.77255470
39	-0.000869916	-0.000853988	-0.605263543	-0.002167815	-0.001944517	-8.485294427	0.00005435	0.00005104	0.33061536	-8.75994261
40	-0.000881713	-0.000865776	-0.605590523	-0.002197739	-0.001973918	-8.505215019	0.00005639	0.00005270	0.36939856	-8.74140699
41	-0.000892947	-0.000877002	-0.605905612	-0.002226237	-0.00200191	-8.524411225	0.00005859	0.00005444	0.41438151	-8.71593533
42	-0.000903635	-0.000887682	-0.606208811	-0.002253346	-0.002028533	-8.542883046	0.00006097	0.00005630	0.46681250	-8.68227936
43	-0.000913789	-0.000897828	-0.60650012	-0.002279102	-0.002053823	-8.560630482	0.00006354	0.00005826	0.52823767	-8.63889293
44	-0.000923423	-0.000907455	-0.606779539	-0.002303541	-0.002077813	-8.577653533	0.00006634	0.00006034	0.60058030	-8.58385277
45	-0.000932552	-0.000916577	-0.607047067	-0.002326695	-0.002100538	-8.593952199	0.00006940	0.00006254	0.68624154	-8.51475772
46	-0.000941186	-0.000925204	-0.607302706	-0.002348596	-0.002122029	-8.60952648	0.00007275	0.00006487	0.78822743	-8.42860175
47	-0.000949339	-0.000933351	-0.607546454	-0.002369275	-0.002142318	-8.624376375	0.00007643	0.00006733	0.91030610	-8.32161673
48	-0.000957021	-0.000941027	-0.607778312	-0.002388761	-0.002161432	-8.638501885	0.00008049	0.00006992	1.05719679	-8.18908341
49	-0.000964244	-0.000948244	-0.60799828	-0.002407081	-0.002179399	-8.651903011	0.00008499	0.00007264	1.23478427	-8.02511702
50	-0.000971018	-0.000955012	-0.608206358	-0.002424262	-0.002196247	-8.664579751	0.00008998	0.00007548	1.45033505	-7.82245106
51	-0.000977352	-0.000961342	-0.608402545	-0.002440329	-0.002211999	-8.676532105	0.00009555	0.00007843	1.71265213	-7.57228252
52	-0.000983257	-0.000967241	-0.608586843	-0.002455305	-0.00222668	-8.687760075	0.00010177	0.00008145	2.03202364	-7.26432328
53	-0.00098874	-0.00097272	-0.60875925	-0.002469212	-0.00224031	-8.69826366	0.00010872	0.00008453	2.41965006	-6.88737285
54	-0.000993809	-0.000977785	-0.608919767	-0.00248207	-0.002252911	-8.708042859	0.00011645	0.00008759	2.88588892	-6.43107370
55	-0.000998473	-0.000982445	-0.609068394	-0.002493899	-0.002264502	-8.717097674	0.00012495	0.00009059	3.43595717	-5.89020890
56	-0.001002738	-0.000986706	-0.609205131	-0.002504716	-0.0022751	-8.725428103	0.00012341	0.00009346	2.99502064	-6.33961260
57	-0.001006611	-0.000990576	-0.609329978	-0.002514539	-0.002284722	-8.733034147	0.00013320	0.00009613	3.70682203	-5.63554210
58	-0.001010097	-0.000994059	-0.609442935	-0.00252338	-0.002293383	-8.739915806	0.00014163	0.00009858	4.30488477	-5.04447397
59	-0.001013202	-0.000997161	-0.609544001	-0.002531255	-0.002301096	-8.746073079	0.00014882	0.00010083	4.79866753	-4.55694955
60	-0.00101593	-0.000999887	-0.609633177	-0.002538176	-0.002307873	-8.751505968	0.00015489	0.00010303	5.18571722	-4.17542193
61	-0.001018286	-0.001002241	-0.609710463	-0.002544151	-0.002313725	-8.756214471	0.00015994	0.00010544	5.44992469	-3.91600025
62	-0.001020274	-0.001004227	-0.609775859	-0.002549192	-0.002318661	-8.76019859	0.00016407	0.00010986	5.42139662	-3.94857783
63	-0.001021896	-0.001005848	-0.609829365	-0.002553306	-0.002322689	-8.763458323	0.00016734	0.00010940	5.79481516	-3.57847253
64	-0.001023155	-0.001007106	-0.60987098	-0.002556499	-0.002325815	-8.765993671	0.00016983	0.00010897	6.08525180	-3.29061285
65	-0.001024053	-0.001008003	-0.609900706	-0.002558776	-0.002328045	-8.767804634	0.00017157	0.00010864	6.29270654	-3.08499880
66	-0.001024591	-0.00100854	-0.609918541	-0.002560141	-0.002329381	-8.768891211	0.00017260	0.00010842	6.41717939	-2.96163037

67	-0.00102477	-0.00100872	-0.609924485	-0.002560596	-0.002329827	-8.769233938	0.00017298	0.00011344	5.95417933	-3.42497910
68	-0.001024591	-0.00100854	-0.609918541	-0.002560141	-0.002329381	-8.768891211	0.00017260	0.00010842	6.41717939	-2.96163037
69	-0.001024053	-0.001008003	-0.609900706	-0.002558776	-0.002328045	-8.767804634	0.00017157	0.00010864	6.29270654	-3.08499880
70	-0.001023155	-0.001007106	-0.60987098	-0.002556499	-0.002325815	-8.765993671	0.00016983	0.00010897	6.08525180	-3.29061285
71	-0.001021896	-0.001005848	-0.609829365	-0.002553306	-0.002322689	-8.763458323	0.00016734	0.00010940	5.79481516	-3.57847253
72	-0.001020274	-0.001004227	-0.609775859	-0.002549192	-0.002318661	-8.76019859	0.00016407	0.00010986	5.42139662	-3.94857783
73	-0.001018286	-0.001002241	-0.609710463	-0.002544151	-0.002313725	-8.756214471	0.00015994	0.00010544	5.44992469	-3.91600025
74	-0.00101593	-0.000999887	-0.609633177	-0.002538176	-0.002307873	-8.751505968	0.00015489	0.00010303	5.18571722	-4.17542193
75	-0.001013202	-0.000997161	-0.609544001	-0.002531255	-0.002301096	-8.746073079	0.00014882	0.00010083	4.79866753	-4.55694955
76	-0.001010097	-0.000994059	-0.609442935	-0.00252338	-0.002293383	-8.739915806	0.00014163	0.00009858	4.30488477	-5.04447397
77	-0.001006611	-0.000990576	-0.609329978	-0.002514539	-0.002284722	-8.733034147	0.00013320	0.00009613	3.70682203	-5.63554210
78	-0.001002738	-0.000986706	-0.609205131	-0.002504716	-0.0022751	-8.725428103	0.00012341	0.00009346	2.99502064	-6.33961260
79	-0.000998473	-0.000982445	-0.609068394	-0.002493899	-0.002264502	-8.717097674	0.00012495	0.00009059	3.43595717	-5.89020890
80	-0.000993809	-0.000977785	-0.608919767	-0.00248207	-0.002252911	-8.708042859	0.00011645	0.00008759	2.88588892	-6.43107370
81	-0.00098874	-0.00097272	-0.60875925	-0.002469212	-0.00224031	-8.69826366	0.00010872	0.00008453	2.41965006	-6.88737285
82	-0.000983257	-0.000967241	-0.608586843	-0.002455305	-0.00222668	-8.687760075	0.00010177	0.00008145	2.03202364	-7.26432328
83	-0.000977352	-0.000961342	-0.608402545	-0.002440329	-0.002211999	-8.676532105	0.00009555	0.00007843	1.71265213	-7.57228252
84	-0.000971018	-0.000955012	-0.608206358	-0.002424262	-0.002196247	-8.664579751	0.00008998	0.00007548	1.45033505	-7.82245106
85	-0.000964244	-0.000948244	-0.60799828	-0.002407081	-0.002179399	-8.651903011	0.00008499	0.00007264	1.23478427	-8.02511702
86	-0.000957021	-0.000941027	-0.607778312	-0.002388761	-0.002161432	-8.638501885	0.00008049	0.00006992	1.05719679	-8.18908341
87	-0.000949339	-0.000933351	-0.607546454	-0.002369275	-0.002142318	-8.624376375	0.00007643	0.00006733	0.91030610	-8.32161673
88	-0.000941186	-0.000925204	-0.607302706	-0.002348596	-0.002122029	-8.60952648	0.00007275	0.00006487	0.78822743	-8.42860175
89	-0.000932552	-0.000916577	-0.607047067	-0.002326695	-0.002100538	-8.593952199	0.00006940	0.00006254	0.68624154	-8.51475772
90	-0.000923423	-0.000907455	-0.606779539	-0.002303541	-0.002077813	-8.577653533	0.00006634	0.00006034	0.60058030	-8.58385277
91	-0.000913789	-0.000897828	-0.60650012	-0.002279102	-0.002053823	-8.560630482	0.00006354	0.00005826	0.52823767	-8.63889293
92	-0.000903635	-0.000887682	-0.606208811	-0.002253346	-0.002028533	-8.542883046	0.00006097	0.00005630	0.46681250	-8.68227936
93	-0.000892947	-0.000877002	-0.605905612	-0.002226237	-0.00200191	-8.524411225	0.00005859	0.00005444	0.41438151	-8.71593533
94	-0.000881713	-0.000865776	-0.605590523	-0.002197739	-0.001973918	-8.505215019	0.00005639	0.00005270	0.36939856	-8.74140699
95	-0.000869916	-0.000853988	-0.605263543	-0.002167815	-0.001944517	-8.485294427	0.00005435	0.00005104	0.33061536	-8.75994261
96	-0.000857541	-0.000841622	-0.604924674	-0.002136425	-0.001913671	-8.464649451	0.00005245	0.00004948	0.29701942	-8.77255470
97	-0.000844573	-0.000828663	-0.604573914	-0.002103529	-0.001881338	-8.443280089	0.00005068	0.00004800	0.26778554	-8.78006846
98	-0.000830995	-0.000815094	-0.604211264	-0.002069086	-0.001847476	-8.421186342	0.00004903	0.00004660	0.24223784	-8.78315977
99	-0.00081679	-0.000800899	-0.603836724	-0.002033052	-0.001812042	-8.39836821	0.00004748	0.00004528	0.21981998	-8.78238495
100	-0.00080194	-0.000786059	-0.603450294	-0.001995382	-0.001774991	-8.374825693	0.00004602	0.00004402	0.20007182	-8.77820417
101	-0.000786427	-0.000770557	-0.603051973	-0.00195603	-0.001736278	-8.35055879	0.00004466	0.00004283	0.18261092	-8.77099985
102	-0.000770233	-0.000754374	-0.602641763	-0.001914949	-0.001695855	-8.325567503	0.00004337	0.00004170	0.16711794	-8.76109133
103	-0.000753338	-0.00073749	-0.602219662	-0.00187209	-0.001653672	-8.29985183	0.00004215	0.00004062	0.15332501	-8.74874649
104	-0.000735722	-0.000719886	-0.601785671	-0.001827402	-0.001609681	-8.273411773	0.00004100	0.00003959	0.14100644	-8.73419100
105	-0.000606711	-0.000606215	-0.018832279	-0.001538853	-0.001509677	-1.108692334	0.00003991	0.00003861	0.12997127	-0.99755334
106	-0.000585637	-0.000585202	-0.01651078	-0.001485513	-0.00145987	-0.974444942	0.00003888	0.00003768	0.12005726	-0.87089846
107	-0.000566119	-0.000565737	-0.014548453	-0.0014361	-0.001413454	-0.860581297	0.00003790	0.00003679	0.11112601	-0.76400374
108	-0.000547986	-0.000547647	-0.01288027	-0.001390181	-0.00137009	-0.763482206	0.00003697	0.00003594	0.10305901	-0.67330347
109	-0.000531088	-0.000530787	-0.011454463	-0.001347382	-0.001329481	-0.680251722	0.00003608	0.00003512	0.09575443	-0.59595176
110	-0.000515299	-0.000515029	-0.01022955	-0.001307383	-0.001291368	-0.608558229	0.00003524	0.00003435	0.08912443	-0.52966334
111	-0.000500506	-0.000500265	-0.00917208	-0.001269904	-0.001255522	-0.546513324	0.00003443	0.00003360	0.08309302	-0.47259239
112	-0.000486616	-0.000486398	-0.008254921	-0.001234704	-0.001221741	-0.492578877	0.00003366	0.00003288	0.07759419	-0.42323961
113	-0.000473542	-0.000473346	-0.007455934	-0.001201571	-0.001189847	-0.445495238	0.00003292	0.00003220	0.07257048	-0.38038069
114	-0.000461213	-0.000461035	-0.006756963	-0.00117032	-0.001159682	-0.404225436	0.00003222	0.00003154	0.06797169	-0.34301071
115	-0.000449562	-0.000449401	-0.006143033	-0.001140786	-0.001131104	-0.367911538	0.00003154	0.00003091	0.06375383	-0.31030074
116	-0.000438533	-0.000438386	-0.005601734	-0.001112826	-0.001103988	-0.335840334	0.00003090	0.00003030	0.05987827	-0.28156380
117	-0.000428075	-0.00042794	-0.005122733	-0.00108631	-0.00107822	-0.307416182	0.00003027	0.00002971	0.05631098	-0.25622794
118	-0.000418142	-0.000418018	-0.004697385	-0.001061123	-0.001053699	-0.282139425	0.00002968	0.00002915	0.05302189	-0.23381492
119	-0.000408693	-0.00040858	-0.004318425	-0.001037164	-0.001030332	-0.259589137	0.00002910	0.00002860	0.04998440	-0.21392316
120	-0.000399693	-0.000399588	-0.003979723	-0.001014339	-0.001008039	-0.239409263	0.00002855	0.00002808	0.04717489	-0.19621410
121	-0.000391108	-0.000391011	-0.003676085	-0.000992567	-0.000986744	-0.221297434	0.00002802	0.00002758	0.04457235	-0.18040117
122	-0.000382909	-0.000382819	-0.003403092	-0.000971773	-0.000966378	-0.204995895	0.00002751	0.00002709	0.04215806	-0.16624093
123	-0.000375069	-0.000374986	-0.003156972	-0.000951888	-0.00094688	-0.19028412	0.00002702	0.00002662	0.03991529	-0.15352580
124	-0.000367564	-0.000367487	-0.00293449	-0.000932852	-0.000928195	-0.176972769	0.00002654	0.00002616	0.03782905	-0.14207820
125	-0.000360372	-0.0003603	-0.002732868	-0.000914609	-0.000910269	-0.164898723	0.00002608	0.00002572	0.03588593	-0.13174566
126	-0.000353473	-0.000353406	-0.002549704	-0.000897108	-0.000893057	-0.153920997	0.00002564	0.00002530	0.03407384	-0.12239686
127	-0.000346849	-0.000346786	-0.002382922	-0.000880303	-0.000876515	-0.143917346	0.00002521	0.00002488	0.03238190	-0.11391836
128	-0.000340482	-0.000340423	-0.002230719	-0.00086415	-0.000860603	-0.134781453	0.00002479	0.00002448	0.03080033	-0.10621185
129	-0.000334357	-0.000334302	-0.002091522	-0.000848612	-0.000845285	-0.126420582	0.00002439	0.00002410	0.02932024	-0.09919186
130	-0.00032846	-0.000328408	-0.001963959	-0.000833652	-0.000830527	-0.118753609	0.00002400	0.00002372	0.02793363	-0.09278394
131	-0.000322778	-0.00032273	-0.001846829	-0.000819237	-0.000816297	-0.111709379	0.00002363	0.00002336	0.02663322	-0.08692299
132	-0.000317299	-0.000317254	-0.001739073	-0.000805336	-0.000802567	-0.105225309	0.00002326	0.00002301	0.02541240	-0.08155198

Table 2. Excel spreadsheet used in calculating the net gravity effect of each cylinder and the total gravity.

Discussion

Although the VAMP structure associated with this study doesn't doesn't display the classic push-downs in the seismic section (Figure 1 – shot gather 3700), which is caused by the decrease in acoustic velocity from the methane gas displacing seawater in the pore space as it buoyantly rises, there is still evidence that for the presence of a methane chimney. The bathymetric map of the study area (Figure 4) has a seafloor topographic low related to the decrease in the gravitational acceleration, which is shown in free-air gravity map (Figure 5). This reinforces the idea that there is a density decefit in the area because as the distance to the center of the Earth decreases, gravity increases. Also, the gravity signature of the gas hydrate alone isn't enough to overcome the basaltic basement high (Table 2), so there must be something else adding to the decrease in the observed gravitational acceleration. An explanation for the lack of a push-down signal could be that the basement high is causing the overlying sedimentary layers above to arch, which is negating the signal that the methane would produce.

A linear trend was fit to the gravity profile (Figure 6) then subtracted from the gravity values to remove the regional effects, leaving the residual gravity (Figure 7). This data was then plotted with the total gravity calculated in Table 2 (Figure 11).

The infinite vertical cylinder approximation in this study is not perfect, but it is a close representation of the observed gravity signal (Figure 11). In this figure, the total gravity of the idealized body plot has a very sharp drop off as it reaches the edges of the cylinder and it more jagged at the central peak caused by the basement high, while the observed gravity has much more gradual drop offs and smooth lines. This could, in part, be attributed to the fact this study only incorporated the gravity effect of a single deposit and didn't factor in the gravitational contributions on either side of the study area.

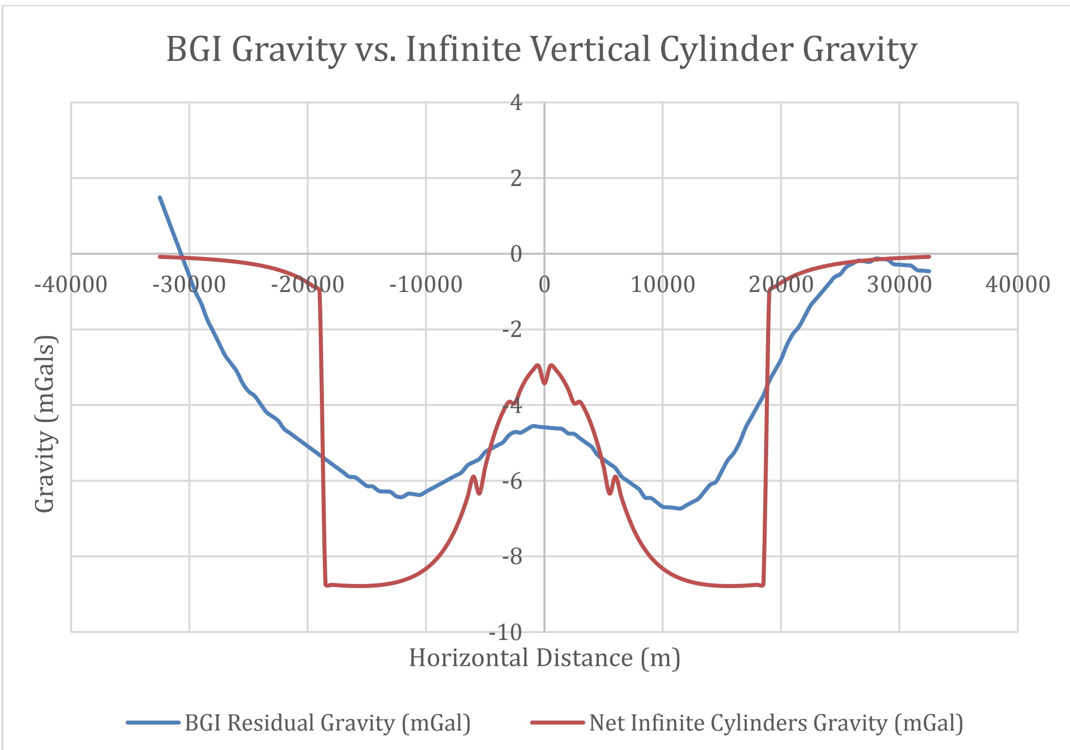

Figure 11. Comparison of the data collected from Oasis Montaj (BGI data set – blue plot) and the MATLAB code used to model the gas hydrate, methane chimney and basement intrusion system (red plot). Gravity values listed in milligals (Y-axis). Horizontal distance is in meters (X-axis).

Conclusions

The objective of this study was to model a gas hydrate deposit, methane chimney and basaltic basement high associated with a VAMP structure in the central Aleutian Basin by approximating each as two infinite vertical cylinders, subtracting the bottom gravity signal from that of the top to produce the total gravity for that deposit and summing the three to get a total gravity signal. This was then related to observed data from a free-air gravity map produced in a geophysical software program.

While the idealized body modeling was not perfect, the plotted data had sharp drop offs at the edges of the cylinder and jagged lines above the basement high, it was successful in producing a signal that was only a few milligals off from the observed data. With some refinement to the code this approach to modeling is a cheap and effective method to reinforce seismic or magnetic data to produce a complete picture of the subsurface.

.

Recommendations for Future Work

Additional methods that could be developed to further this research would be to:

A) Model the other significant basement highs, methane chimneys and methane hydrate deposits to get a complete, coherent view of the gravity data.

B) The infinite vertical cylinder method might be more effective if it was conducted in an area where there weren't significant basement highs or other methane hydrates in proximity, adding or subtracting from the gravity signal.

C) Create a more sophisticated code for computing the gravity effects as a whole, instead of breaking them down into their constituent parts then attempting to combine the results.

Other types of idealized bodies could be used to determine subsurface features, such as a sphere to model karst systems or a horizontal cylinder to approximate tunnels or other horizontal, linear features which display density differences from the surrounding country rock.

References Cited

Balmino, G., Vales, N., Bonvalot, S. and Briais, A., 2012. Spherical harmonic modeling to ultra-high degree of Bouguer and isostatic anomalies. *Journal of Geodesy*. July 2012, Volume 86, Issue 7, pp 499-520 , DOI 10.1007/s00190-011-0533-4.

Bonvalot S., Balmino G., Briais A., Kuhn M., Peyrefitte A., Biancale R., Gabalda G., Reinquin F., Sarrailh M., 2012. World Gravity Map. Commission for the Geological Map of the World. Eds. BGI-CGMW-CNES-IRD, Paris.

Cooper AK., Scholl DW., Marlow MS., Childs JR., Redden GD., et al. (1979) Hydrocarbon potential of Aleutian Basin, Bering Sea. *Am Assoc Pet Geol Bull* 63: 2070-2087.

Expedition 323 Scientists. (2010) Bering Sea paleoceanography: PliocenePleistocene paleoceangraphy and climate history of the Bering Sea. *IODP Prel Rept 323*.

Hinze W.J., von Frese R.R.B., Saad A.H. (2012) *Gravity and Magnetic Exploration: Principles, Practices, and Applications.*

Li X, He S. (2011) Progress in Stability Analysis of Submarine Slopes Considering Dissociation of Gas Hydrates. *Environ Earth Sci,* 66:741–747

MATLAB and Statistics Toolbox Release 2016b, The MathWorks, Inc., Natick, Massachusetts, United States.

Rabinowitz P, Cooper AK. (1977) Structure and Sediment Distribution in the Western Bering Sea. *Marine Geology*, 24: 309-320

Scholl DW, Cooper AK. (1978) VAMPs- possible hydrocarbon-bearing structures in Bering Sea basin. *Am Assoc Pet Geol Bull* 62: 2481-2488.

Shankar U, Thakur N.K., Khanna R. (2003) Gravity signatures of gas hydrate. *Current Science*, Vol. 85, No. 4.

Stabeno P.J., Schumacher J.D., Ohtani K. (1999) Dynamics of the Bering Sea: a summary of physical, chemical, and biological characteristics, and a synopsis of research in the bering sea. North Pacific Marine Science Organization (PICES), University of Alaska Sea Grant, AK-SG-99-03, 1-28.

Yankovsky E., Terry D., Knapp C. (2015) Seismic and Gravity Evidence for Methane-Hydrate Systems in the Central Aleutian Basin. *Int J Earth Sci Geophys* 2015, 1:1